A Traffic Density Analysis of Proposed Ferry Service Expansion in San Francisco Bay Using a Maritime Simulation Model

Jason R. W. Merrick*

Department of Statistical Sciences and Operations Research

Virginia Commonwealth University

PO Box 843083, 1001 West Main St., Richmond, VA 23284

J. Rene van Dorp

Joseph P. Blackford

Gregory L. Shaw

Jack Harrald

Thomas A. Mazzuchi

Department of Engineering Management and Systems Engineering

The George Washington University

1776 G St. NW, Suite 110

Washington, DC, 20052

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* Corresponding Author. Phone: (804) 828 1301 ext. 136, Fax: (804) 828 8785 Email: jrmerric@vcu.edu.

Abstract

A proposal has been made to the California legislature to dramatically increase the frequency and coverage of ferry service in the San Francisco Bay area. A major question in the approval process is the effect of this expansion on the level of congestion on the waterway and the effect this will have on the safety of vessels in the area. A simulation model was created to estimate the number of vessel interactions in the current system and their increases caused by three alternative expansion plans. The output of the simulation model is a geographic profile showing the frequency of vessel interactions across the study area, thus representing the level of congestion under each alternative. Comparing these geographic interaction profiles to a similar one generated for the current ferry service in the San Francisco Bay allows evaluation of the increase in exposure of ferries to adverse conditions, such as, for example, the interaction of high speed ferries in restricted visibility conditions. This analysis has been submitted to the legislature as part of the overall assessment of the proposal and will be used in the expansion decision.

Keywords: Maritime Transportation; Simulation; Safety; Accident prevention.

1. Introduction

In an effort to relieve congestion on freeways, the state of California is proposing to expand ferry operations on San Francisco (SF) Bay by (1) phasing in up to 100 ferries in addition to the 14 currently operating, (2) extending the hours of operation of the ferries, (3) increasing the number of crossings, and (4) employing some high-speed vessels. The state of California has directed the San Francisco Bay Area Water Transit Authority (WTA) to produce an *Implementation and Operations Plan (IOP)*, part of which requires working with the U.S. Coast Guard (USCG), the California Maritime Academy (CMA), and SF Bay Area ferry operators in preparing a "plan for ensuring safety of vessel operations traveling on the San Francisco Bay." The purpose of this plan is to realistically evaluate the levels of safety relative to various aspects of ferry operation.

In the process of developing the safety plan the WTA used data from the Federal Transit Administration National Transit database to describe the current safety level. Federal databases describe the past safety performance of the existing ferry services. Between 1996 and 2000, ferry service appeared to be the safest federally subsidized transit mode in the San Francisco Bay Area. The WTA's comparison showed that ferry transportation had: (1) No fatalities for patrons, employees, or others (i.e., bystanders). The average for the rail and roadway transit modes was 0.004 fatalities per 1,000,000 passenger miles; (2) Less than one-fourth the patron injury rate of the rail and roadway transit modes. Ferry operations averaged 0.28 injuries per 1,000,000 passenger miles; (3) about two-thirds the bystander injury rate of the rail and roadway transit modes. Ferry operations averaged 1.5 injuries per 1,000,000 vehicle miles; (4) On average 5.6 reported accidents per 100,000 transits, or 3.8 reported accidents per year for the 10-year period from 1992 to 2001; this is in line with the rates for similar marine transportation systems.

The WTA safety plan further documents a wide range of risks and associated risk controls. For risks and necessary risk controls that are already documented in codes, standards, and regulations, the plan provides a very brief overview. In conclusion, the safety plan indicates that analysis of the existing ferry services show that those services provide safe transit and are currently effectively managing risks. However, the question remains whether this “safe” operation can continue with the new pressures of aggressive service expansion. The three proposed expansion scenarios are: (1) Alternative 3: Enhanced Existing System; (2) Alternative 2: Robust Water Transit System and (3) Alternative 1: Aggressive Water Transit System. From these, Alternative 3 is the least aggressive expansion scenario and Alternative 1 is the most aggressive one. The WTA tasked the author’s to investigate the impact of ferry service expansion on maritime traffic congestion in the SF Bay area by developing a maritime simulation model of the SF Bay. Due to time and budget constraints a full-scale risk assessment, such as the authors’ previous work in the Prince William Sound Risk Assessment [1, 2, 3] or the Washington State Ferries Risk Assessment [4, 5], was not feasible. In these studies, a simulation of the traffic and weather patterns was used to count interactions between the vessels and an expert judgment based accident probability model was used to estimate the likelihood of a collision if such an interaction occurs. Instead, to assess the impact of aggressive ferry expansion, the scope of the San Francisco Bay study was limited to the simulation part of the model, leaving the accident probability part to a later project if the expansion proposal is approved.

Limiting the scope of the analysis to interactions, however, will still allow meaningful conclusions regarding potential effect of the ferry service expansions on observed collision rates. In fact, interactions are known to be one of the drivers in collision risk (see, e.g., [5]); an increase in interactions will typically result in an increase in collision risk if additional risk interventions are not put in place. The purpose of the simulation is to assess the interactions of vessels in the current ferry system and to compare their geographic profile to the interactions seen under the proposed scenarios. For instance, if the daily volume of ferry transits increases ten-fold does the number of interactions increase ten-fold? Is it possible that, since the proposed alternatives include new routes to new areas of the SF Bay, the additional interactions are distributed in such a manner that no additional high-traffic density areas occur that could indicate safety problems? Due to its unique visibility conditions, one of the main safety concerns in the SF Bay is transiting through restricted visibility. If there are additional high-traffic density areas, do they perhaps occur in restricted visibility conditions? The simulation study in this paper attempted to answer such critical safety questions.

An outline of the paper is as follows. Previous work in maritime risk assessment and simulation are discussed in Section 2. Sections 3, 4, and 5 discuss the construction of the simulation, specifically the interaction-counting model in Section 3, vessel movements in Section 4 and restricted visibility modeling in Section 5. The results of the study are outlined in Section 6. Conclusions and recommendations are presented in Section 7.

2. Literature Review

The National Research Council has repeatedly identified the assessment and management of risk in maritime transportation as an important problem domain [6, 7, 8, 9]. In earlier work, researchers concentrated on assessing the safety of individual vessels or marine structures, such as nuclear powered vessels [10], vessels transporting liquefied natural gas [11], and offshore oil and gas platforms [12]. The USCG has used a classical statistical analysis of nationwide accident data to prioritize federal spending to improve port infrastructures [13, 14]. More recently, researchers have used probabilistic risk assessment (PRA) [15] in the maritime domain [16, 17, 18, 19, 20, 21, 22, 23] by examining risk in the context of maritime transportation systems [9].

In a maritime transportation system (MTS), traffic patterns change over time in a complex manner. Researchers have used system simulation as a modeling tool to assess MTS service levels [24], to perform logistical analysis [25], and to facilitate the design of ports [26]. The dynamic nature of traffic patterns and other situational variables, such as wind, visibility, and ice conditions, mean that risk levels change over time. Recent probabilistic risk assessments [27] in the maritime domain have used simulation to model the dynamic nature of the transportation system.

The Prince William Sound Risk Assessment [1, 2, 3] used a simulation of the oil transportation system to evaluate changes in the dynamic pattern of traffic caused by proposed risk intervention measures, such as weather-based closure conditions for certain parts of the transit and modifications to the tug escort service put in place to save disabled tankers from running aground. Accident and incident data was augmented using expert judgment to take the simulations interaction counts and arrive at estimates of accident frequency and the expected volume of oil outflow. The Washington State Ferries Risk Assessment [4, 5] used an improved version of the technique, but with the consequence of interest being passenger safety rather than environmental damage.

As mentioned previously, the study in this paper used the simulation part of this approach to only assess the impact of ferry expansion on the level of vessel interactions in the Bay. If the expansion proposal is approved, the simulation analysis can be extended to a full probabilistic risk assessment through an accident probability model based on available accident, incident data and expert judgments.

3. The Simulation: Interaction Counting Model

In the simulation program, a snapshot of the simulation is taken every minute; counts of the interactions are taken and recorded in an event database. Figure 1 shows such a snapshot of the San Francisco Bay maritime simulation. Moving boats are represented by the triangles. Which pairs of vessels are interacting? This depends on both the distance between the vessels the time until the vessels meet.

The interaction model is based on Closest Point of Approach (CPA) type arguments and stems from the considerations that a ferry captain will make when considering interactions with other vessels. For example, vessels close in at different speeds, thus in evaluating a situation involving other vessels, a captain is interested in which will arrive first, not necessarily which is closest.

Consider a ferry transiting through the system. As a default, any other vessel within a half a nautical mile[†] of the ferry is counted as interacting; half a nautical mile is

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[†] 1 nautical mile equals approximately 1.15 miles

too close for comfort to most professional mariners. If another vessel is more than half a mile away and in addition is more than five minutes away from crossing the track of the ferry, it is not counted as an interaction. If a vessel is within five minutes of crossing the ferry track and in addition this crossing will occur within 1 nautical mile in front of the ferry or within half a mile behind the ferry, the vessel is counted as interacting with ferry. Experts with maritime experience outside the ferry service and a group of ferry captains from the Washington State Ferry Service provided input for this methodology [5, 28].

The snapshot of the simulation at a specific time is analyzed to determine whether the ferries in the system are interacting with other vessels (including other ferries) using the interaction model above. For each interaction found, the information about the type of the other vessel, the type of interaction (crossing, meeting or passing), the visibility conditions and the coordinates of the vessels are recorded and written to an interaction database. This database is then used to find the number of interactions occurring in a simulation run in each of a grid of cells across the San Francisco Bay.

This information can then be represented in the form of a colored map, with the colors representing the number of interactions in each cell of our grid. This map may be interpreted as a geographic profile of ferry interactions. The color gradient for the grid cells is established using a simulation of the current ferry service on the San Francisco Bay (to be referred to as the Base Case). The Base Case analysis allows existing trouble spots to be identified, thereby not attributing these to the planned ferry service expansions. Next, using the Base Case color scale, similar geographic profiles can be generated for these expansions. Emerging hot spots resulting from the expansions can be visually observed by comparing their geographic profile to that of the Base Case. For further discussion of the interaction-counting model, see [27].

4. The Simulation: Vessel Movement

To achieve an accurate count of the number of interactions, we must have an accurate simulation of the vessel movements. This means we need an accurate background map of the Bay, an accurate representation of the movement of the ferries themselves and an accurate representation of the movements of the other vessels in the Bay. The background map of the maritime simulation model for the San Francisco Bay area (see Figure 1) was constructed from NOAA electronic charts, which were converted to bitmaps for use with the simulation program. This allowed accurate representation of the vessel coordinates and speed.

Ferry movements for the base case simulation were obtained from ferry schedules collected from ferry operators for the years 1998-2001. Each proposal for expansion of the ferry service included the number of transits per day, the time between transits, and the start time. At the current stage of the proposed expansions, the schedules are simply defined by operations starting at 6 am and running every 15, 30, or 60 minutes depending on the route.

The ferry routes configurations for the base case simulation and proposed expansions were obtained from GIS maps created by the URS Corporation for the WTA. In all, 18 ferry routes were considered for the base case simulation and up to 64 ferry routes for the proposed expansion alternatives. The cruising speed of each ferry class along their route is a known, constant speed when underway. The ferries slow down when leaving and entering dock. Ferries also slow in restricted visibility. Ferries that usually maintain between 25 and 35 knots will reduce speed to 12 knots. Slower excursion ferries will slow to 10 knots. These speeds were determined in discussions with ferry captains and were confirmed by the ferry companies. To reflect this behavior in the simulation model, restricted visibility needs to be represented adequately. The modeling of visibility conditions in the simulation is discussed in the next section.

In building maritime simulation models, non-ferry traffic is usually modeled by analyzing traffic arrival/departure data to construct probability distributions for vessel inter-arrival times. These distributions are then used to simulate vessel arrivals and transits in the system [27]. However, the presence of the San Francisco Vessel Traffic System (SF VTS) eliminated the need for this approach. Data on date, time, and transits for 6000 routes for up to 26 different vessel types were obtained from the VTS for the 1998-2001 period. Waypoint data obtained from the SF VTS was used in conjunction with the bitmap of the San Francisco Bay area to produce the total vessel transit picture. Figure 2 illustrates an example of the routes of a particular class of vessels. Again average vessel speeds for each class are maintained during transits with the exception of vessels slowing down in restricted visibility. Average vessel speed information was obtained through personal communication with SF Bar Pilots. In restricted visibility, deep-draft traffic slows to about 70% of its usual transit speed. This rule was determined by discussions with members of the SF Bay Pilot's Association and operators from the VTS. These databases of traffic arrivals and routes were read in to the simulation program, removing the problem of validation of arrivals models [28].

Unfortunately, the SF VTS does not routinely record the movements of small vessels such as recreational yachts. As at certain times this can be the most numerous type of traffic on the Bay, special events, such as regattas, were modeled in the simulation as well. The USCG supplied their Marine Event List for over 1000 special events for the year 2001. Due to time and budget constraints only the main type of special events were modeled in the maritime simulation, i.e. 828 scheduled regattas in 2001. The data on regatta times and areas were obtained from the USCG data. Through discussions with the SF VTS, 13 locations were defined for these regatta events. Regattas were modeled by blocking the defined areas (see Figure 3) during their times and dates and then randomly moving the assigned number of participating vessels within each area.

5. The Simulation: Restricted Visibility

Restricted visibility conditions have a significant impact on the pattern of traffic in the SF Bay in part due to the channel fog phenomenon at the Golden Gate Bridge during the third quarter of the year. To model these traffic patterns, visibility conditions were modeled in the simulation and, as mentioned previously, the movements of vessels were modified depending on these conditions. For the purposes of visibility modeling, the San Francisco Bay area was divided into five regions; Golden Gate, San Pablo Bay, Alameda, South Bay and Grizzly Bay. The locations for visibility were defined using a square-grid breakdown of the study area. Figure 4 identifies the different visibility locations used in the maritime simulation model. The location definitions displayed in Figure 4 were in part used to model the phenomenon of channel fog observed at the Golden Gate Location. Hourly wind speed and direction data is recorded via NOAA buoys for the period 1998-2001 at the five locations as well as dew point and water temperature data. Visibility data, however, is not gathered and thus a visibility model had to be developed.

The visibility model used in the simulation is based on a model described in [29]. The model stated that if the dew point is above the water temperature, then visibility will be restricted, otherwise the visibility will be good. In such a model, visibility is defined as good if it is greater than or equal to 0.6 miles and bad otherwise. Dew point and water temperature are recorded by the NOAA buoys, making such modeling of visibility possible. Rather than using this definition, we adhere to the rules of the road definition of restricted visibility (i.e. vessel operators are required to use their fog signals). A calibration constant was introduced into the visibility model to allow for this disparity, requiring the difference between the dew point and the water temperature to be above the calibration constant for such restricted visibility conditions to occur.

The calibration constant for the Golden Gate location for the third quarter of the year (July, August and September) was calculated from the US Coast Pilot's [30] data. The US Coast Pilot [30] states that restricted visibility conditions occur at Golden Gate approximately 20% of the time during the third quarter, the worst quarter for visibility in the Golden Gate location. However, no percentages are provided in the US Coast Pilot for the remaining quarters of the year; only anecdotal data is provided. Expert judgment was used to determine the calibration constants for restricted visibility conditions in the remaining three quarters at Golden Gate by comparing them to the third quarter. The experts involved were 7 operators from the SF VTS and 5 SF Bar Pilots with extensive experience throughout the SF Bay Area.

The process followed to elicit the remaining calibration constants utilizes the well known Analytical Hierarchy Process (AHP) [31, 32]. Figure 5 provides an example pair wise comparison question used in this process. Each expert is asked to assess whether restricted visibility is more likely in the quarter on the left hand side or that on the right hand side and by how much. The experts' assessments are used to calculate a relative multiplier for each quarter. By simple averaging of each expert's assessed values, for example, the resulting relative multiplier for the first quarter of the year was 0.258. This means that the experts indicated that the percentage of time that restricted visibility conditions occur in the first quarter of the year at Golden Gate should be 0.258 times the 20% of the third quarter (for which data was available) or 5.17%. Figure 6 provides the results for the location Golden Gate. Note the (perhaps remarkable) agreement between the US Coast guard VTS experts and SF Bar Pilots displayed in Figure 6 for the remaining quarters of the year.

The green line in Figure 6 indicates the percentages that were used for calibration of the modified visibility model [29] for the Golden Gate location. Figure 7 provides the monthly model results for this location for the year 2000. Note that, in the third quarter (July, August and September) the model reflects early morning fog that burns off during the late morning hours and early afternoon hours and reestablishes itself during the late afternoon. The latter daily pattern is typical for the channel fog phenomenon for this quarter at the Golden Gate location (see, e.g., US Coast Pilot [30]).

No visibility data, in terms of percentage of time that restricted visibility occurs, was available for the remaining locations San Pablo Bay, Alameda, South Bay and Grizzly. Hence, we had to rely once again on expert judgment to determine calibration constants for restricted visibility conditions. We followed the same process as above, comparing these four locations by quarter to the previously established percentage of time that restricted visibility occurs in Golden Gate (see, Figure 6). For example, a multiplicative factor of 2.397 was assessed for the location San Pablo Bay during the first quarter of the year when compared to the Golden Gate location. Utilizing the previously established 5.17% for restricted visibility in Golden Gate during this quarter, the percentage of time that restricted visibility occurs in San Pablo bay was set at 2.397 times 5.17% or 12.38%. Table 1 provides the estimated percentages of time that restricted visibility occurs by quarter of the year and by location. The information in Table 1 was used to calculate the calibration constants for the visibility model for the remaining locations, San Pablo Bay, Alameda, South Bay and Grizzly.

6. Results

Figure 1 shows a screen shot of the simulation program created to perform the vessel interaction analysis. For a more detailed look, movies of the simulation for each of the cases can be viewed at http://www.people.vcu.edu/~jrmerric/SFBayMovies/. Recall that the simulation was intended to answer certain specific questions. For the defined scenarios, what is the increase in the number of interactions involving ferries? What is the increase in the area in which such interactions occur? Are there any high-density areas that could be a cause of concern, either in the current ferry system or in any of the proposed scenarios? As interactions in restricted visibility are of particular concern, what is the affect of the proposed scenarios on frequency and density of such interactions?

We will start our discussion of the results of the simulation analysis with some basic comparisons to current ferry operations. The current ferry operations, or the Base Case, are used as a reference point to compare the proposed alternatives and to give an understanding of the traffic patterns currently seen by ferries in the study area. Figure 8 summarizes the analysis findings. Observe from Figure 8 that the number of ferry to vessels interactions grows exponentially with the number of ferry transits, not linearly. This result was somewhat of a revelation for the WTA. Table 2 gives the detail of the comparison of the three alternative cases to the Base Case.

Alternative 3 (the least aggressive expansion) has 3.65 times as many transits as the Base Case, but covers only a little larger area, with 16% more grid cells having at least one interaction in them in the simulation. In all over 6 times as many interactions occur in Alternative 3 than occurred in the Base Case, while the coverage area of these interactions only increases by a factor of 1.16. Thus Alternative 3 makes the current operating area more congested with more interactions. In addition, the fourth row in Table 2 displays results for Alternative 3 counting only those interactions that occur in restricted visibility. Note that, 1.10 times as many interactions occur in Alternative 3 in restricted visibility than the whole Base Case (regardless of visibility). Moreover, these interactions cover only 91% of the coverage area in the Base Case and are thus more concentrated. We will return to this important observation.

Alternative 2 has 12.28 times as many transits as the Base Case, but covers a much larger area, with 2.33 times as many grid cells having at least one interaction. In all over 46 times as many interactions occur in Alternative 2 than occurred in the Base Case. Thus Alternative 2 increases the operating area from the Base Case and leaves the system much more congested with many more interactions. Finally, Alternative 1 (the most aggressive expansion) has 15.59 times as many transits as the Base Case, but covers only a little larger area than Alternative 2, with 2.4 times as many grid cells having at least one interaction than in the Base Case. In all over 83 times as many interactions occur in Alternative 1 than occurred in the Base Case. Thus Alternative 1 increases the operating area by about the same factor as Alternative 2, but significantly increases congestion with many more interactions compared to Alternative 2.

Figures 9 shows the geographic interaction profile for the Base Case. The Base Case ferry routes are shown in color. Figure 9 is quite complex, as it attempts to convey all the Base Case results in one figure. We will examine the pieces of Figure 9 one by one. The analysis is broken down across a grid of approximately ¼ mile by ¼ mile cells. The cells are color coded in Figure 9 to represent the number of interactions that occur in that cell over the 1-year simulation time. Both the cell containing the ferry and the cell containing the interacting vessel are recorded; hence the colored cells away from the ferry routes.

To the right of Figure 9, the legend gives an interpretation for the color-coding of the cells. The scale goes from blue, with the fewest interactions, to black with the most interactions. The solid black cell has the most interactions of any cells in the Base Case simulation. This Base Case maximum is used as a reference point for the legend. The percentages shown in the legend are calculated as a percentage of this maximum number of interactions. For example, an orange cell has an interaction count that is only 3% of the maximum number of interactions observed in a grid cell in the Base Case. Another reference scale is also provided. The average number of interaction per cell in the Base

Case has 1.68% of the maximum number of interactions in a cell observed in the Base Case. Returning to our example, an orange cell has 1.78 times the number of interactions seen in the average cell in the Base Case. A solid black cell, with the most interactions, has over 60 times as many interactions as the average in the Base Case, indicating that some cells are highly congested when compared to the average cell. One can also see that the legend is not numerically linear. Since some of the cells are much more congested than others, we have had to develop a color gradient following a power curve to highlight their differences.

What can we learn about the current ferry operations, or Base Case, from Figure 9? The majority of the dark colored grid cells are in the Central Bay area, particularly close to the Ferry Building. In fact, if we take the red square around the Ferry Building, almost 53% of all the interactions in the Base Case occur in this area. This is the area with most ferries, a great deal of other VTS Traffic and organized recreational events operating, combined with the worst visibility for a large part of the year (especially in the third quarter of each year).

Figures 10 and 11 examine Alternative 3 (the least aggressive expansion) and Alternative 1 (the most aggressive expansion) and compare their results to the Base Case in the same figures. A similar geographic interaction profile was generated for Alternative 2 (the future ferry expansion between Alternative 1 and Alternative 3). Note that the legend has not changed to allow the comparison to the Base Case. Notice that the same red square around the Ferry Building in Alternative 3 (Figure 10) now contains 3.7 times as many interactions as the whole Base Case and that much of the area within the red square is now colored solid black, indicating that there are more interactions in those grid cells than the maximum for any grid cell in the Base Case. Similar conclusions can be drawn from Figure 11 illustrating the geographic interaction profile for Alternative 1 (the most aggressive expansion of future ferry service.) Notice that, the same red square around the Ferry Building now contains approximately 27 times as many interactions as the whole Base Case and again much of the area is colored solid black, indicating that there are more interactions in those grid cells than the maximum for any grid cell in the Base Case.

Of particular concern are interactions that occur in restricted visibility. Recall from Table 2 that 1.10 times as many interactions occur in Alternative 3 in restricted visibility than the whole Base Case (regardless of visibility). Moreover, these interactions cover only 91% of the coverage area in the Base Case. Figure 12 displays the results for Alternative 3 counting only those interactions that occur in restricted visibility. Concentrating on the red square in Figure 12, it follows that 57.92% of the interactions in the whole Base Case (regardless of visibility) are now occurring in the red square in restricted visibility conditions in Alternative 3. In the Base Case, 6.57% of the total interactions occurred in restricted visibility in the red square. Hence, although Alternative 3 (the least aggressive ferry expansion) resulted in an increase from the Base Case of 3.65 times as many interactions overall, an approximate increase of 8.82 (= 57.92%/6.57%) times as many interactions are observed in the red square in Figure 13 in restricted visibility. These restricted visibility interactions involve both regular and high-speed ferries in an area that is already the most congested in the Base Case. Findings of this nature should be of concern to those planning for future ferry expansions.

7. Conclusions and Recommendations

The analysis discussed herein is only one part of the overall assessment of the proposed ferry service expansion by the WTA. Digital movies of the simulation were requested by the WTA allowing the decision-makers to visualize the reality of their proposed ferry service expansions. In addition, other projects are underway or have been completed examining environmental issues, ferry terminal expansions, ridership, intermodal transportation issues, and new technologies [see http://www.watertransit.org]. Each of these studies will be summarized in the *Implementation and Operations Plan* to be submitted to the California Legislature on December 12th 2002, with review continuing through the summer of 2003.

The vessel interaction analysis presented in this paper provides a foundation for examining the risk inherent in such a major expansion of service and is a first step in a full risk assessment that would satisfy the requirements of the US Coast Guard Captain of the Port. The vessel interaction analysis results can be combined in follow on steps with a conditional accident probability model and an accident damage model for an overall estimate of MTS accident risk [5]. These results, however, do give an initial indication of where high accident risk spikes may occur by illustrating the occurrences of added congestion and their location. In addition, the results seem to indicate that the safety levels currently enjoyed by the SF Bay ferry service cannot be maintained under the planned expansion scenarios without equally aggressive investment in risk intervention. With the broader picture of risk in mind, the project team made the following recommendations to the WTA at the conclusion of the project:

1. Use the results of the simulation analysis in a Probabilistic Risk Assessment (PRA) similar to that of the Washington State Ferry Risk Assessment, where output analyses is presented in terms of expected number of accidents per year.
2. Consider the current San Francisco Bay Ferry Operations and future planned ferry operations as a Maritime Transportation System (MTS) rather than a collection of individual ferry routes by:
    a. Designing a ferry traffic routes system that allows for increased ferry traffic while limiting the increase in expected number of accidents per year.
    b. Designing ferry schedules utilizing this ferry traffic route system that allow for increased ferry traffic while limiting the increase in expected number of accidents per year. A consideration in the development of these future schedules should be the time between arrivals and departures at ferry terminals to allow for sufficient time of loading and unloading passengers.
3. Develop other risk intervention measures that can reduce the number of interactions and the probability of accidents given an interaction.
4. Investigate the effect of proposed risk intervention measures on the accident probability using the full probabilistic risk assessment model.
5. Perform an uncertainty analysis of accident risk and risk intervention evaluation to provide estimates of annual accident risk and risk intervention effectiveness in terms of probability intervals rather than point estimates.

"The truth is that we are uncertain. The language of uncertainty is probability. Therefore, speaking the truth means to develop analyses results in terms of probability curves rather than in terms of point estimates." [33]

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Figure 1. A Snapshot of the SF Bay Maritime Simulation Model.

Figure 2. Vessel Routes for LPG Vessels in the SF Bay Maritime Simulation Model.

Figure 3. Definition of Regatta Locations in the SF Bay Maritime Simulation Model.

Figure 4. Definition of Visibility Locations in the SF Bay Maritime Simulation Model: Golden Gate (Red), San Pablo Bay (Green), Alameda (Blue), South Bay (Purple) and Grizzly Bay (Maroon).

Figure 5. Example Pair wise Comparison Question for the Location Golden Gate.

Figure 6. Restricted Visibility Analysis Results for the Location Golden Gate for the First Quarter of the Year (J-F-M), Second Quarter (A-M-J), Third Quarter (J-A-S) and Fourth Quarter (O-N-D).

Figure 7. Hourly Percentages of Restricted Visibility for the Location Golden Gate by Month.

Figure 8. Exponential Growth in Interactions due to Ferry Service Expansion.

Figure 9. The full Base Case Simulation Results.

Figure 10. The full Alternative 3 Simulation Results.

Figure 11. The full Alternative 1 Simulation Results.

Figure 12. Alternative 3 Results Counting only Restricted Visibility Interactions.

Table 1. Estimated Percentages of Time that Restricted Visibility Occurs by Quarter and by Location

	First Quarter J - F- M	Second Quarter A - M - J	Third Quarter J - A- S	Fourth Quarter O - N - D
Golden Gate	5.17%	11.66%	20.00%	6.69%
San Pablo Bay	12.38%	6.17%	6.30%	9.62%
Alameda	7.49%	7.61%	10.61%	7.02%
South Bay	4.92%	5.00%	5.53%	4.74%
Grizzly Bay	14.40%	5.17%	5.34%	11.06%

Table 2. Percentage comparisons to the Base Case under various criteria.

	% Base Case Ferry Transits	% Base Case Grid Cells Covered	# Base Case Total Interactions
Base Case	100%	100%	100%
Alternative 3	365%	116%	624%
Alternative 2	1228%	233%	4620%
Alternative 1	1559%	240%	8359%
Alternative 3 -BVI	-	91%	110%

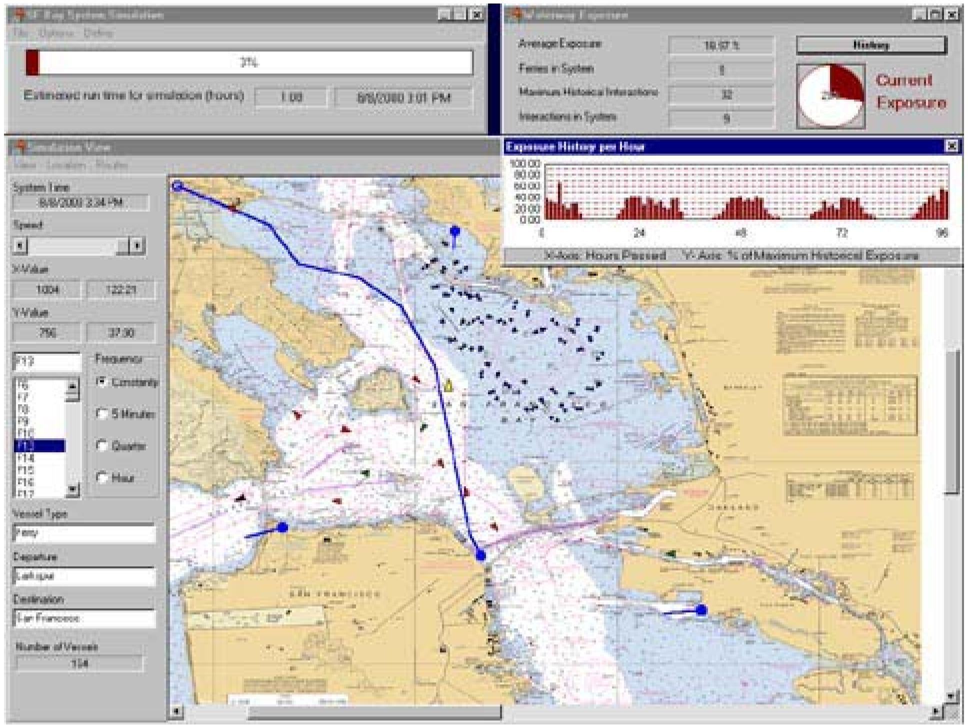

Figure 1. A Snapshot of the SF Bay Maritime Simulation Model.

Figure 2. Vessel Routes for LPG Vessels in the SF Bay Maritime Simulation Model.

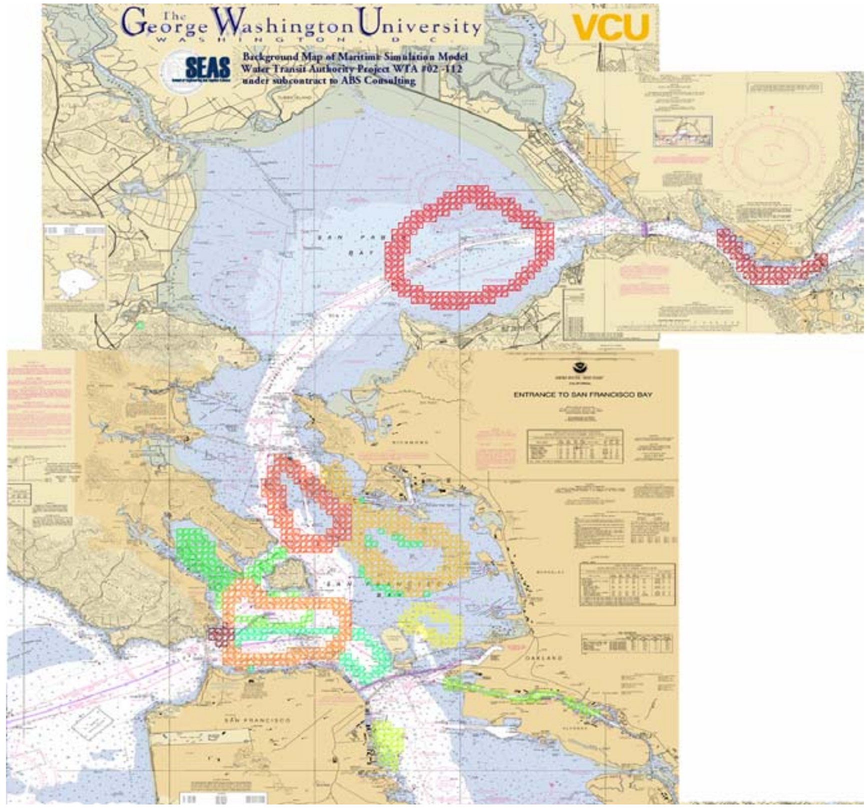

Figure 3. Definition of the various Regatta Locations in the SF Bay Maritime Simulation Model.

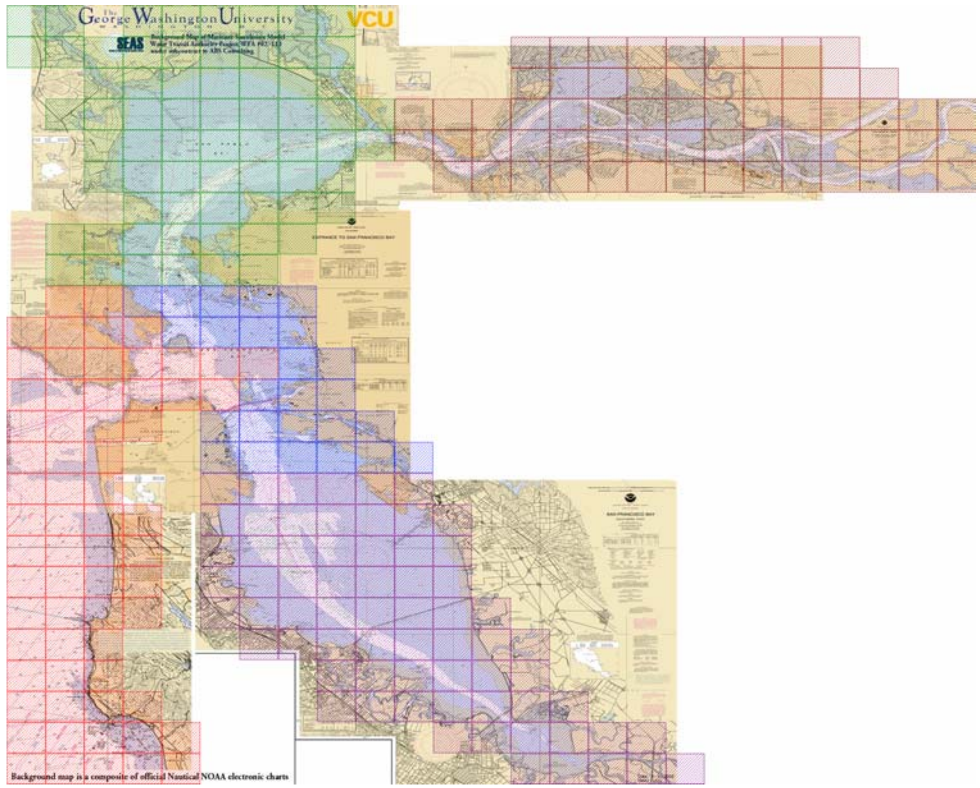

Figure 4. Definition of Visibility Locations in the SF Bay Maritime Simulation Model:

Golden Gate (Red), San Pablo Bay (Green), Alameda (Blue), South Bay (Purple) and Grizzly Bay (Maroon).

Please compare the two quarters in terms of the percentage of time that vessels operate in restricted visibility (i.e. vessels are required to use their fog signal) in the specified Location.

LOCATION: Golden Gate

Quarter **Jan - Feb - Mar** **Left Hand Side More**	**Quarter** **Jul - Aug - Sep** **Right Hand Side More**

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

1 Same amount of time
3 Three times more
5 Five times more
7 Seven times more
9 Nine times or more

Figure 5. Example Pair wise Comparison Question for the Location Golden Gate.

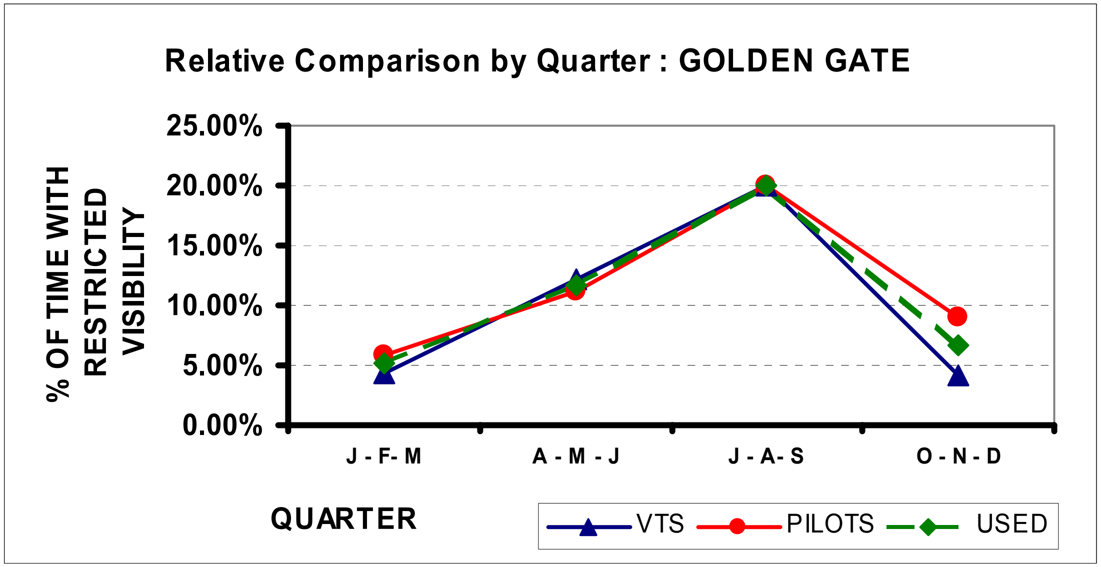

Figure 6. Restricted Visibility Analysis Results for the Location Golden Gate for the First Quarter of the Year (J-F-M), Second Quarter (A-M-J), Third Quarter (J-A-S) and Fourth Quarter (O-N-D). The green line indicates the percentages that were used for calibration.

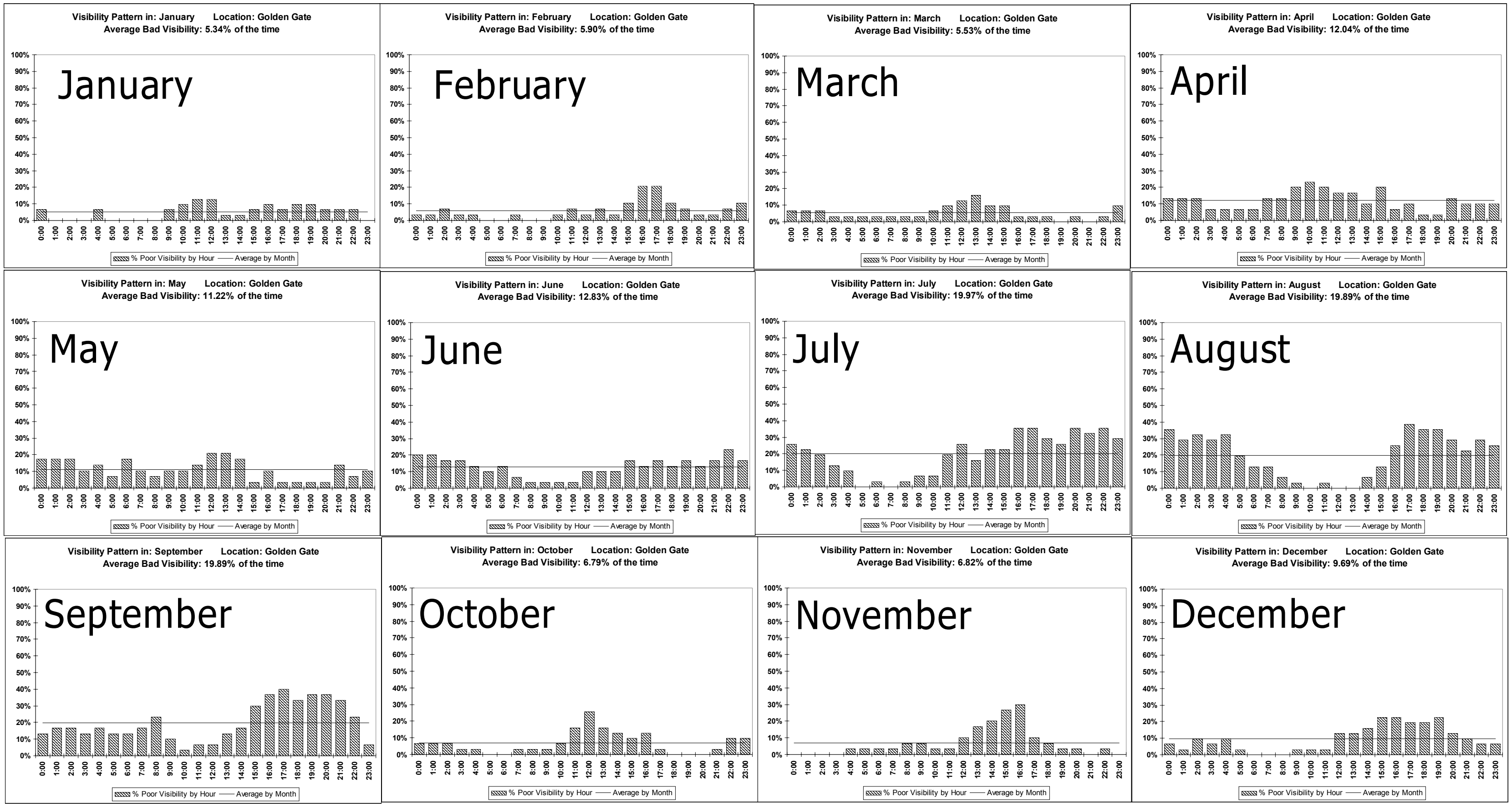

Figure 7. Hourly Percentages of Restricted Visibility for the Location Golden Gate by Month.

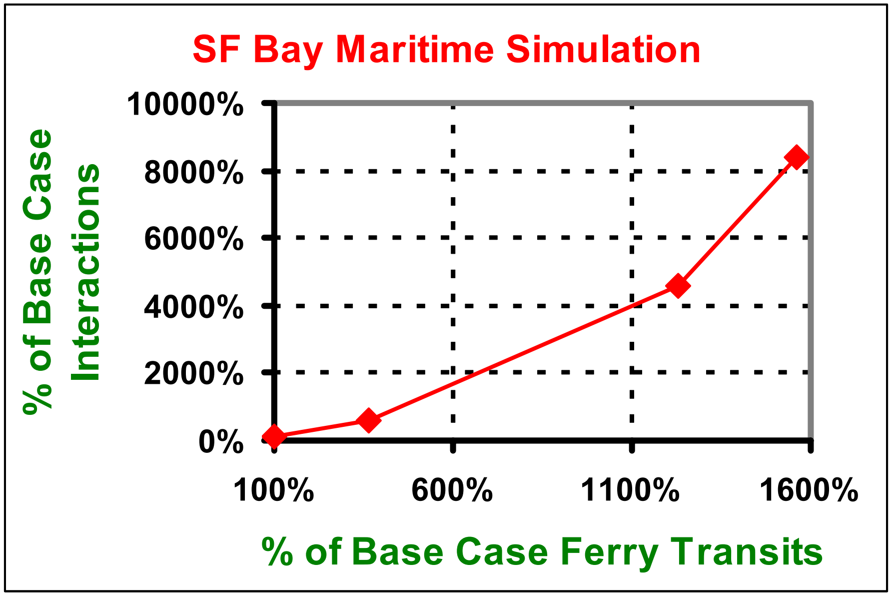

Figure 8. Exponential Growth in Interactions due to Ferry Service Expansion.

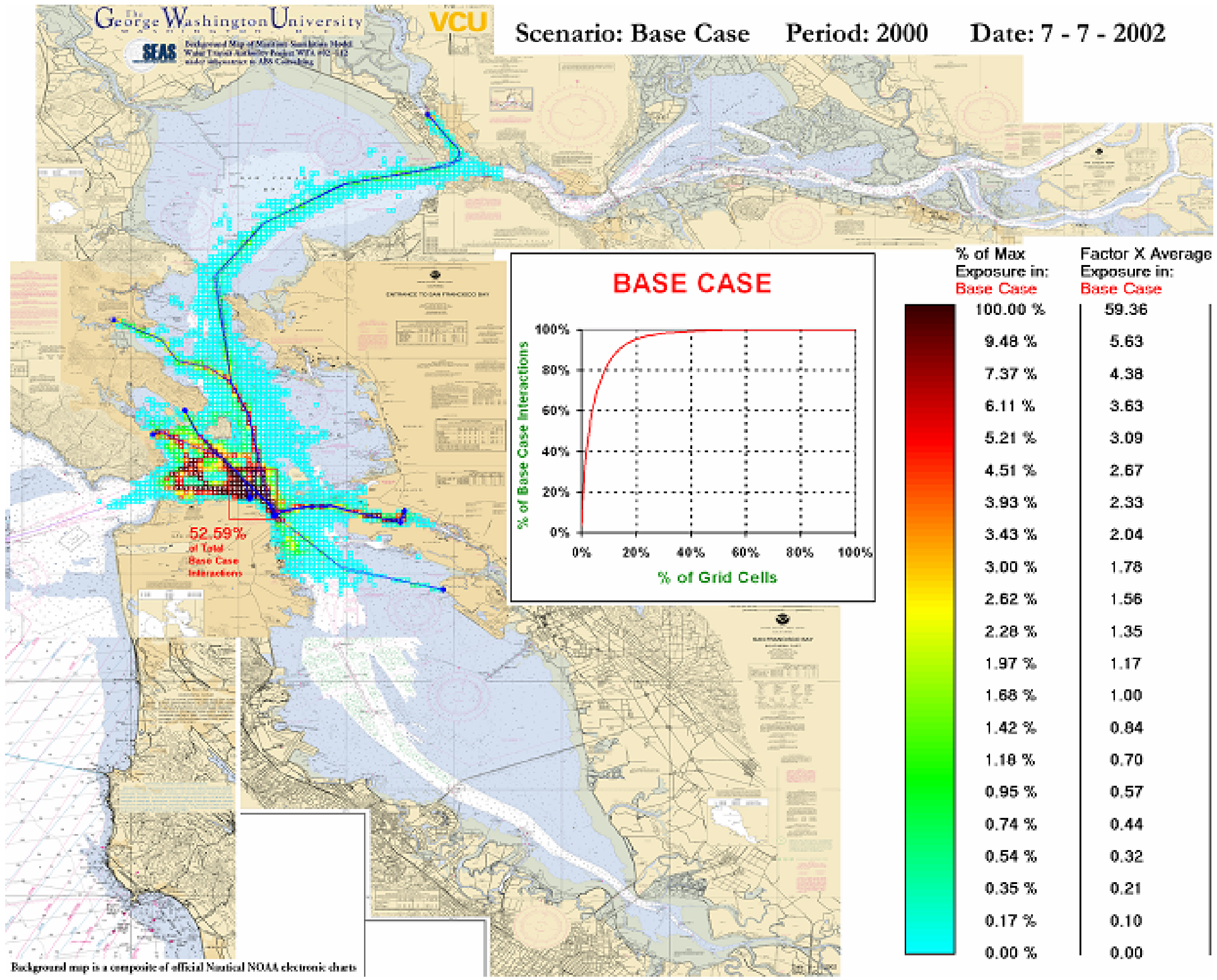

Figure 9. The full Base Case Simulation Results.

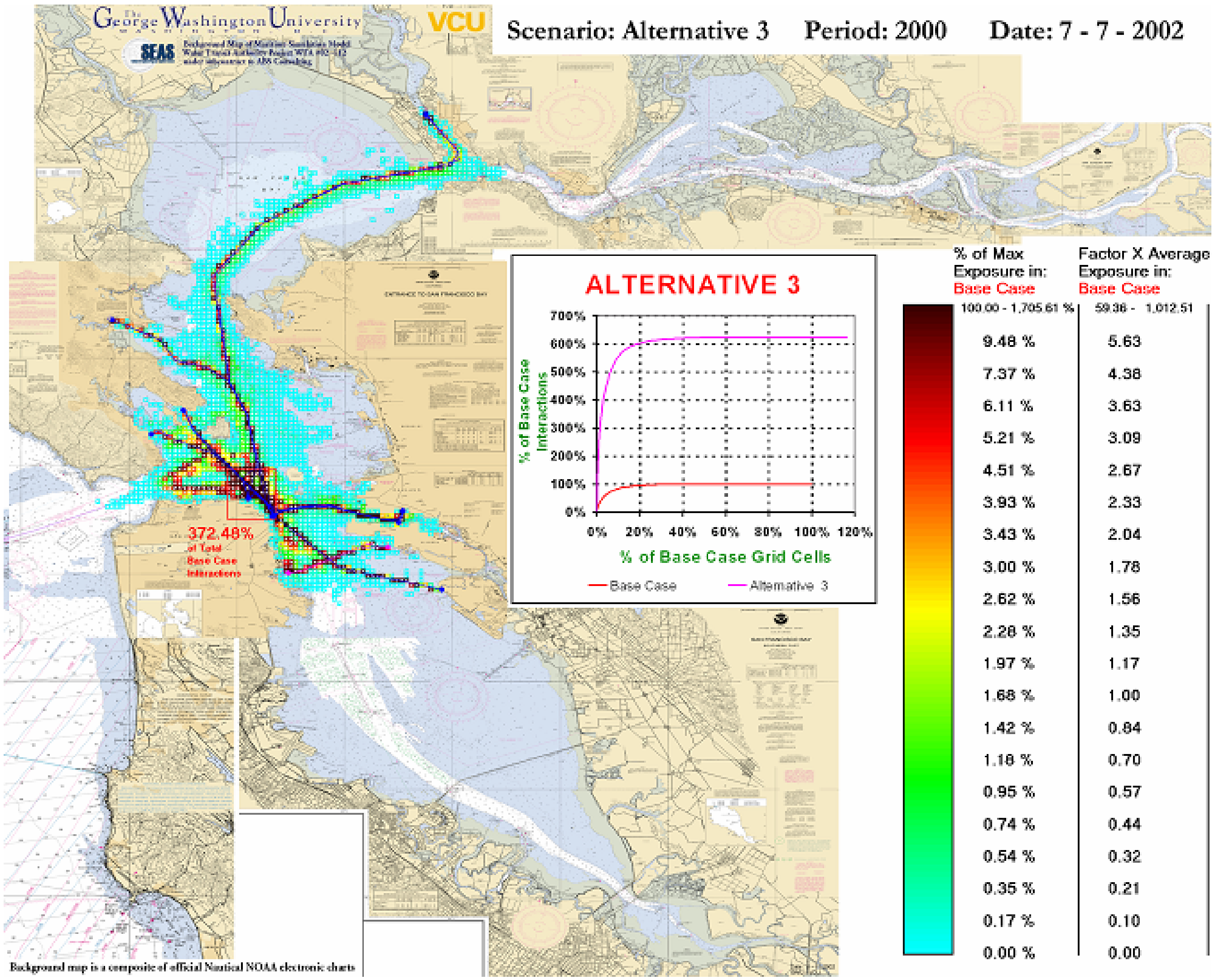

Figure 10. The full Alternative 3 Simulation Results.

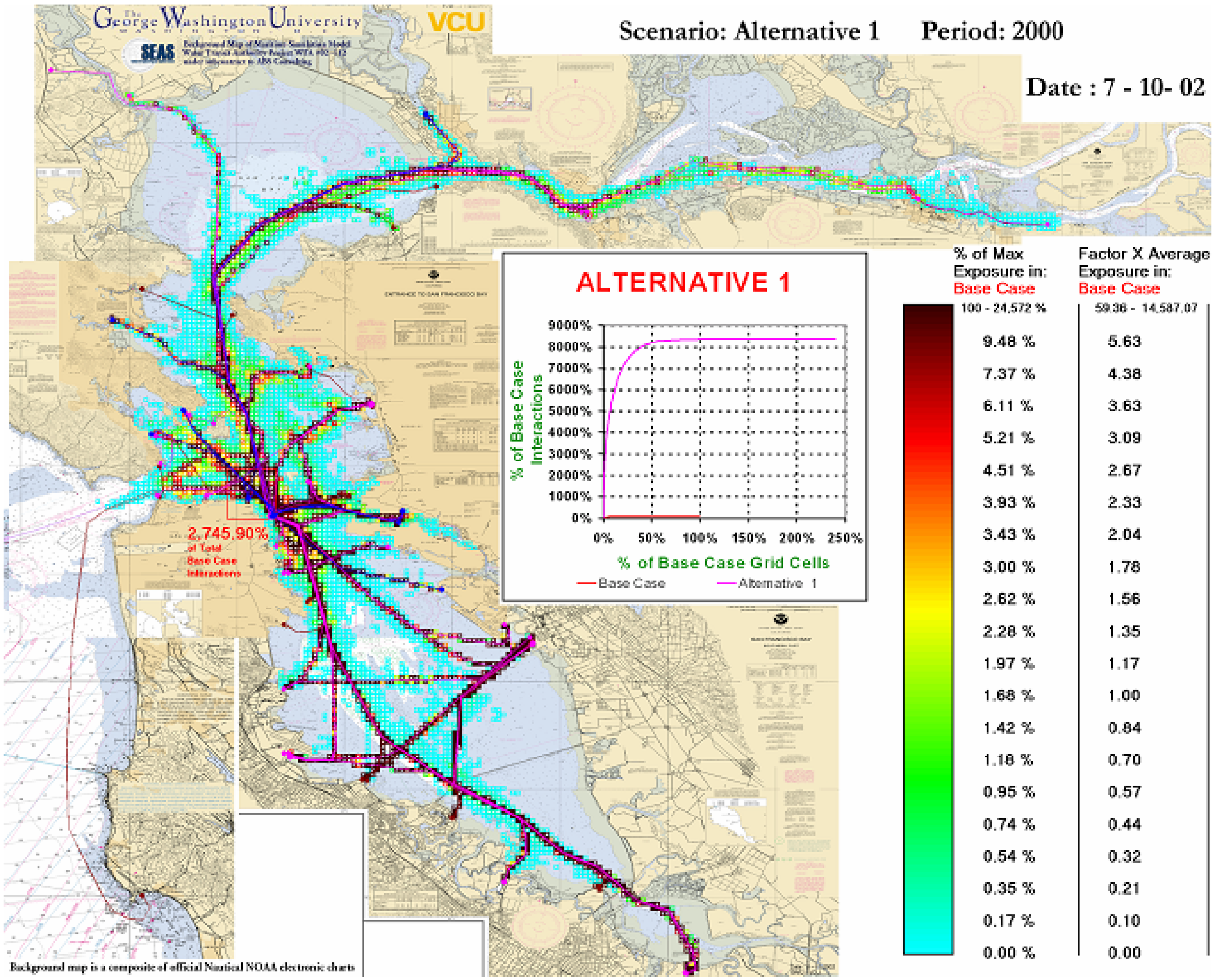

Figure 11. The full Alternative 1 Simulation Results.

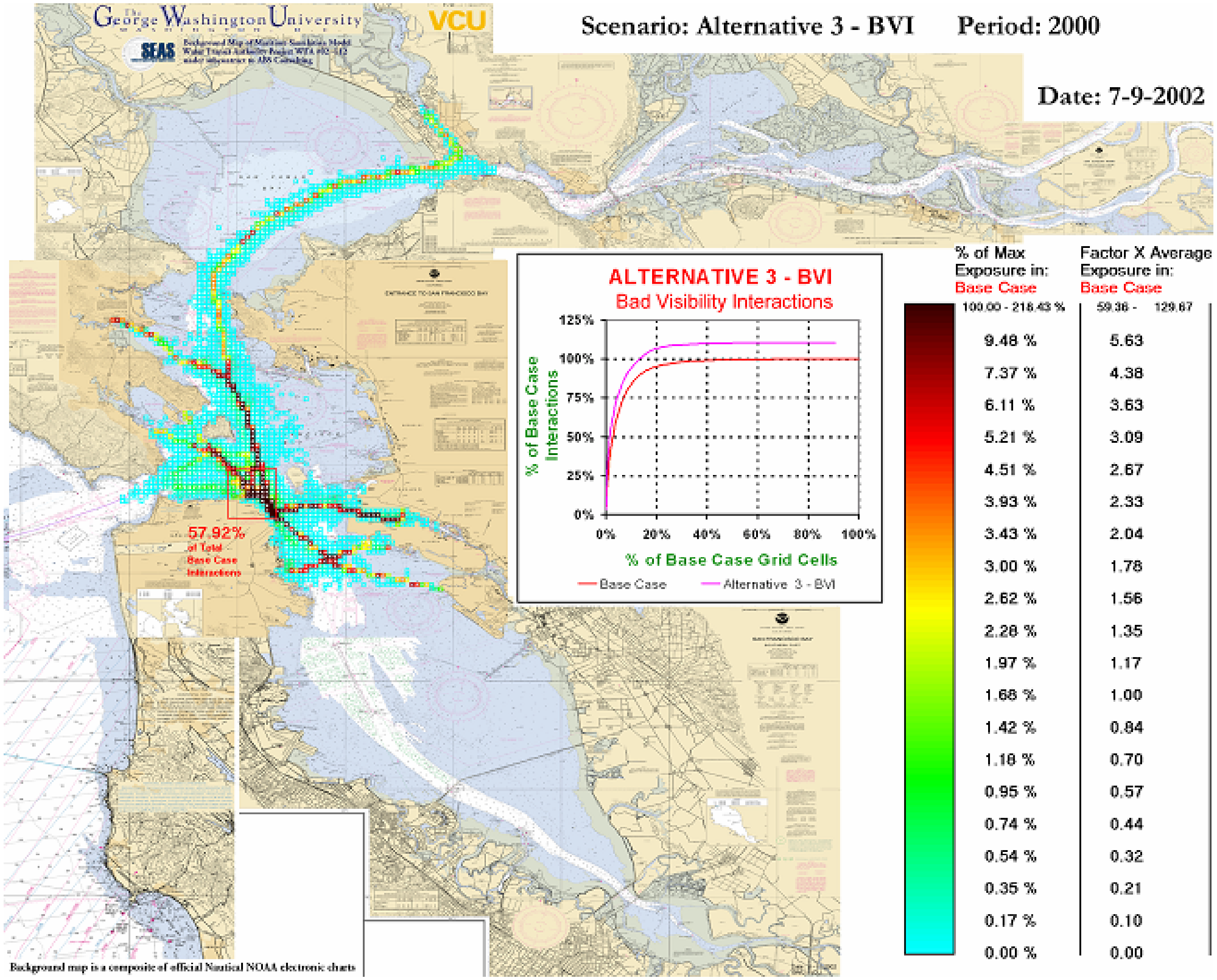

Figure 12. Alternative 3 Results Counting only Restricted Visibility Interactions.